Updraft Gasification of Salmon Processing Waste

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ABSTRACT: The purpose of this study was to judge the feasibility of gasification for the disposal of waste streams generated through salmon harvesting. Gasification is the process of converting carbonaceous materials into combustible "syngas" in a high temperature (above 700 °C), oxygen deficient environment. Syngas can be combusted to generate power, which recycles energy from waste products. At 66% to 79% moisture, raw salmon waste streams are too wet to undergo pyrolysis and combustion. Ground raw or de-oiled salmon whole fish, heads, viscera, or frames were therefore "dried" by mixing with wood pellets to a final moisture content of 20%. Ground whole salmon with moisture reduced to 12% moisture was gasified without a drying agent. Gasification tests were performed in a small-scale, fixed-bed, updraft gasifer. After an initial start-up period, the gasifier was loaded with 1.5 kg of biomass. Temperature was recorded at 6 points in the gasifier. Syngas was collected during the short steady-state period during each gasifier run and analyzed. Percentages of each type of gas in the syngas were used to calculate syngas heating value. High heating value (HHV) ranged from 1.45 to 1.98 MJ/kg. Bomb calorimetry determined maximum heating value for the salmon by-products. Comparing heating values shows the efficiency of gasification. Cold gas efficiencies of 13.6% to 26% were obtained from the various samples gasified. Though research of gasification as a means of salmon waste disposal and energy production is ongoing, it can be concluded that pre-dried salmon or relatively low moisture content mixtures of waste with wood are gasifiable.

Keywords: biomass, calorimetry, salmon

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Introduction

According to the Food and Agriculture Organization of the United Nations (FAO), about 15% of the animal protein consumed by the entire human population comes from seafood. Fish consumption in 2003 totaled over 104 million tonnes worldwide, or 16.5 kg of fish per capita. Three-fourths of this total was finfish (FAO 2006), and a large percentage of this, especially in the northern Pacific, came from salmon.

The wild catch of salmon in Alaska totaled almost 339000 metric tons per year on average from 1998 to 2002 (Woodby and others 2005). Crapo and Bechtel (2003) reported a wild catch of 320 metric tons. According to Bower and Malemute (2005) marine fishing operations in Alaska may be discarding up to 60% of their landed catch weight as processing waste. However, for salmon processing, waste generation is typically about 27% (Crapo and Bechtel 2003). Using this estimate, 86000 to 92000 metric tons per year of salmon by-products are processing waste. This makes by-product development an important topic in the Alaska fishery industry. There are less than a hundred facilities in the state, which combined, produce about 45000 metric tons of fish meal and 7000 metric tons of fish oil annually from the by-products of the total Alaskan catch (AOFD 2007). These by-products derive from all species in Alaskan commercial fishing. However, most of these facilities are located around the larger fishing villages, such as Dutch Harbor and Kodiak, or at sea in fishing trawlers. In the rural fishing villages, where much of the salmon is caught, there are few, if any, alternatives for by-product handling short of returning it back into the natural food chain through a process formally referred to as "at-sea discharge" where the waste is ground and pumped out to sea. The Magnuson-Stevens Act (M-SFCMA 2007) has tightened restrictions on at-sea discharge and set a system of fines to ensure the amount of waste discarded in the ocean decreases and the amount converted to value-added by-products increases.

The objective of this study was to evaluate gasification technology as a method for adding value to salmon by-products. Gasification is the process of converting a solid, organic feedstock in a high temperature, oxygen deficient atmosphere to a mixture of gases, known as syngas or producer gas. To be functional, syngas must contain enough hydrogen, carbon monoxide, methane, and other flammable hydrocarbons to be combusted in a later stage, such as a boiler or Integrated Gasification Combined Cycle (IGCC) system (reference). Applying this technology to salmon by-products will allow the rural Alaskan processing plants to not only reduce their at-sea discharge but also offset energy costs by using the syngas in a boiler generator system.

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Materials and Methods

Sample preparation

Red Salmon (*Oncorhynchus nerka*) whole fish, heads, and viscera were collected from a Kodiak fish processing facility and transported to the Fishery Industrial Technology Center in Kodiak, Alaska, for further processing. Collection of Red Salmon frames occurred at a later, more convenient time because it is uncommon for processors to fillet salmon.

Collected samples included 30 whole salmon, heads, viscera, or frames. Each type of sample was ground and homogenized using a Biogrind model 7540 (CMI Corp., Oklahoma City, Okla., U.S.A.) with a 1.27 cm (1/2 inch) plate. A portion of each sample was collected for either drying or de-oiling. Dried samples were prepared by placing them in a Littleford steam-jacketed, vacuum dryer (Littleford Day, Inc., Florence, Ky., U.S.A.) at 25 inches mercury for 4 to 5 h at

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54.4 °C to decrease moisture. De-oiled samples were prepared by heating homogenized samples at 95 °C for 50 min to extract oil then centrifuging for 20 min at 16500 times gravity using a Beckman J2-HS centrifuge (Fullerton, Calif., U.S.A.) equipped with a JA-20 rotor. All samples were then frozen for transport to Oklahoma State Univ. Before freezing (−20 °C), portions of homogenized treated (dried and de-oiled) and untreated (raw) samples were set aside for composition and energy content analysis.

Composition and energy content analysis

Moisture content of salmon was determined gravimetrically on a wet basis. Approximately 1 to 5 g of wet sample were placed in dry aluminum cups in a drying oven at 103 °C for 24 h. Protein was measured by drying samples and analyzing for nitrogen content on an Elementar Rapid NIII analyzer (Mt. Laurel, N.J., U.S.A.) using WINRAPID(TM) software to calculate protein values. Lipids were determined by processing dried samples on a Soxtec Model 2043 using a methylene chloride extraction solvent, after which, lipid-rich solutions were evaporated to dryness to remove solvent, and then weighed. Ash content was determined gravimetrically after drying samples in a muffle oven (500 °C, 24 h).

Energy content of salmon was determined using a Parr 6200 Calorimeter with Parr 6510 Water Handling System (Parr Instrument Co., Moline, Ill., U.S.A.) according to established Parr Instrument Co. protocols (2008). Mineral oil was used to aid combustion for samples that combusted incompletely when unaided.

Gasification

System startup and operation procedures as outlined in Bowser and others (2005) were followed for each gasifier session with the following modifications: 400 g of 100% pine pellets (Lone Star Bedding, Clifton, Tex., U.S.A.) soaked in 20 mL of charcoal lighter fluid were used to provide startup heat. Ports were closed to retain heat. Compressed air was supplied at a constant rate of 3.4 m^3/h. Pellets were allowed to burn for about 18 min until a maximum bed temperature (approximately 750 °C) was reached before 1.5 kg of feed material was loaded. The scraper operated for 15 s every 10 min. Gas samples were taken at 10, 20, and 30 min after loading biomass. Tar was not measured subjectively as quantitative collection was not feasible.

Preliminary tests to determine highest optimum moisture content for gasification in the gasifier (Bowser and others 2005) consisted of consulting available experts and testing various moisture content samples in the gasifier. Tests in the gasifier included gasifying an entire 1.5 kg sample and analyzing the syngas. Groundwork investigation determined the highest moisture content of red salmon by-products and pellet mixture that would effectively gasify in the test-scale gasifier was 20%. Fish was mixed with pellets to reduce moisture to 20% immediately prior to loading biomass into gasifier. The salmon/pellet mixture was mixed as thoroughly as possible without breaking down the pellet structure. Table 1 reports the amount of fish in each 1.5 kg mixture of biomass loaded into the gasifier. The balance of the 1.5 kg was wood pellets. The samples without a number in Table 1 were not gasified. Dried heads and frames and de-oiled viscera were generally too dense and molasses-like to burn properly in the gasifier. No pellets were necessary for the dried whole fish mixture because dried whole fish had a moisture content of 11.9%.

Table 1 — Amount of salmon waste in the 20% mc mixtures for gasification. The remainder of the 1500 g of biomass loaded in the gasifier was pellets.

	Whole fish	Heads	Frames	Viscera
Raw	348	367	355	310
Dried	1500	na	na	952
De-oiled	370	399	362	na

na = denotes a treatment which was not used for gasification.

Syngas (synthesis gas) analysis

Syngas samples were taken through an outlet at the elbow of the gas exhaust pipe (Bowser and others 2005) with a gas-tight syringe (Cole Parmer, Vernon Hills, Ill., U.S.A.). Syngas was injected into the gas chromatograph for analysis with the instrument setup reported by Cateni and others (2003) with the only modification being Helium added to the analysis. Each salmon treatment was gasified in 4 replications.

Statistical analysis

Treatment effects were investigated using one-way analysis of variance (ANOVA). Composition and bomb calorimetry analysis was conducted with the Statistica v 7.1 software package (Statsoft, Tulsa, Okla., U.S.A.). All other results were analyzed using the SigmaStat 3.0 (SPSS, Inc., Chicago, Ill., U.S.A.). Mean separation was achieved using Tukey's Studentized range Honestly Significantly Different (HSD) for multiple comparison of means. Tests were conducted at significant level of $\alpha = 0.05$.

Results and Discussion

Composition

Moisture contents of homogenized salmon varied from 66.9% to 78.5% for untreated (raw) samples (Table 2). For treated samples, moisture contents varied from 0.1% to 28.8% for the dried samples and 61.9% to 78.6% for de-oiled samples (Table 2). Only 1 data point was obtained for dried frames. Raw and de-oiled frames had the highest variations with 1.61 and 2.22 standard deviations, respectively. Heads had the greatest decrease in moisture content when treated: 66.9% to 0.1% when dried and 66.9% to 61.9% when de-oiled. Heads also had the lowest moisture content and viscera had the highest moisture content in each of the 3 treatments. Viscera also saw the least amount of change in moisture content when treated: 78.4% to 28.8% when dried and 78.4% to 78.6% when de-oiled. De-oiled samples had lower moisture contents than raw samples for each type of salmon waste except viscera. Moisture content of pellets was 4.8%. Moisture contents of salmon by-products were similar to those found by Bechtel (2003). Quaak and others (1999) report that biomass with moisture content as high as 63% is currently being used commercially to generate energy with an updraft gasifier. Because of the high moisture content, an updraft gasifier would be necessary for gasifying salmon, as downdraft gasifiers require feedstock moisture content to be less than 25% and open-core gasifiers less than 15% (Quaak and others 1999). With proper design considerations, the drying zone (Figure 1; FAO 1986) could be enlarged to allow for the high moisture content of salmon waste. However, with the test-scale gasifier used in this study, 20% moisture was the highest that could be tested. Higher moisture contents resulted in too dense of a biomass waste that did not flow down properly through the heating bed. Results from analysis of lipid, protein, and ash contents (Table 2) of Red Salmon were similar to those reported for Pink Salmon as reported by Bechtel (2003).

Bomb calorimetry measurements

Energy contents of ground salmon varied from 5.29 to 24.4 MJ/kg for raw, 16.5 to 26.2 MJ/kg for dried and 4.95 to 23.8 MJ/kg for de-oiled samples (Table 3). Drying the samples significantly increased energy content for all samples except frames. De-oiled whole fish and heads had higher energy contents than their raw counterparts, while de-oiled frames and viscera had lower energy contents than raw counterparts. If a fish oil facility is in production in the area where gasification of salmon by-products is occurring, the most value might be added to the by-products by first de-oiling then gasifying. The correlation between energy content and lipid content would then affect the gasification process. Crossin and Hinch (2005) reported somatic energy content of adult sockeye salmon. Their data demonstrated a strong correlation between energy content and lipid content. The energy content of the population they sampled ranged from 4 to 12 MJ/kg. In the current study, the energy content for untreated red (sockeye) salmon was reported as 7.87 MJ/kg with a lipid content of 7.1%. For similar lipid contents, Crossin and Hinch (2005) reported energy values around 7 MJ/kg. These values are also similar to those reported in the USDA Nutrient Database (USDA-ND 2008) for the edible portion of sockeye salmon (7.3% lipid; 6.41 MJ/kg). Energy content of pellets was taken as 18.8 MJ/kg (Rao 2004). The energy content of waste evaluated in the current study is comparable to that reported by Bowser and others (2005) on biomass collected from bacon and frankfurter production. The biomass they tested was sludge collected from dissolved air flotation units with a heating value of 26 MJ/kg and a reported lipid content of about 14%.

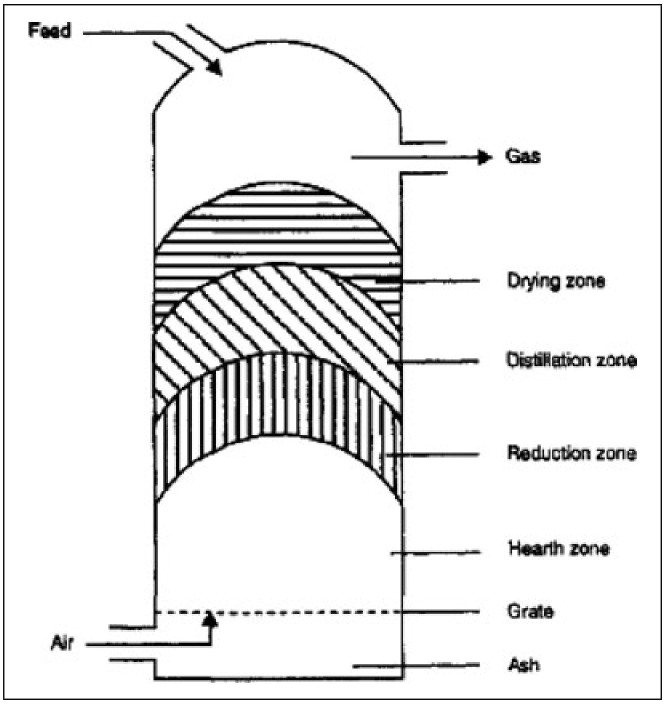

Figure 1—Zones biomass passes through in an updraft gasifier (FAO 1986).

Gasification

Thermocouples at 2 positions in the gasification chamber (Bowser and others 2005) allowed for logging the temperature every 30 s. Procedures for gasification were designed to model steady-state conditions in a production-scale gasifier. Figure 2 is a graph of a typical temperature plot obtained from the combustion chamber thermocouples. It is clear that steady-state conditions were not achieved. This unsteady temperature state adds a degree of uncertainty to all measurements made during gasification.

Table 4 displays percentages of gases in syngas produced from the various treatments. High percentages of nitrogen (N_2) are due to the compressed air introduced at the base of the gasifier for combustion. Oxygen (O_2) in syngas indicates sampling error as all oxygen introduced in compressed air is used for combustion and pyrolysis of biomass. High-energy gases that indicate good quality syngas are hydrogen (H_2), carbon monoxide (CO), methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4), and ethane (C_2H_6). Analysis of syngas from pure wood pellets was comparable to syngas composition reported in similar studies (WRBEP 2002). Analysis of Syngas from pellets was not similar to results reported by Bowser

Table 2—Composition of salmon by-products.

	Whole fish	Heads	Frames	Viscera
Moisture				
Raw	70.2 ± 0.04^{g}	66.9 ± 0.50^{f}	69.0 ± 0.90^{fg}	78.5 ± 0.27^{h}
Dried	12.0 ± 0.05^{c}	0.09 ± 0.01^{a}	6.7 ± 0.20^{b}	28.8 ± 0.27^{d}
De-oiled	66.5 ± 0.26^{f}	61.9 ± 0.33^{e}	67.7 ± 1.3^{fg}	78.6 ± 0.20^{h}
Lipid				
Raw	7.1 ± 0.16^{bc}	15.4 ± 0.92^{e}	6.3 ± 0.29^{abc}	2.6 ± 0.11^{a}
Dried	26.5 ± 0.18^{f}	50.9 ± 2.49^{g}	24.5 ± 0.18^{f}	12.9 ± 0.23^{de}
De-oiled	9.3 ± 0.07^{cd}	15.5 ± 0.55^{e}	8.7 ± 0.18^{c}	3.2 ± 0.07^{ab}
Protein				
Raw	20.7 ± 0.38^{d}	13.2 ± 0.20^{a}	18.5 ± 0.22^{c}	15.9 ± 0.11^{b}
Dried	59.0 ± 0.40^{h}	39.2 ± 0.10^{f}	58.0 ± 0.45^{h}	53.6 ± 0.57^{g}
De-oiled	23.1 ± 0.37^{e}	15.1 ± 0.35^{b}	23.7 ± 0.10^{e}	15.7 ± 0.44^{b}
Ash				
Raw	2.8 ± 0.64^{bc}	3.3 ± 0.19^{cd}	4.5 ± 0.33^{def}	1.6 ± 0.02^{a}
Dried	5.2 ± 0.08^{efg}	12.0 ± 0.22^{h}	11.5 ± 0.09^{h}	5.7 ± 0.06^{g}
De-oiled	2.2 ± 0.14^{abc}	5.4 ± 0.03^{fg}	4.1 ± 0.16^{de}	1.7 ± 0.04^{ab}

Data represent means and standard errors.
Means within same analyte without common superscript are different ($P < 0.05$).

Table 3—Energy content (MJ/kg) of salmon by-products.

	Whole fish	Heads	Frames	Viscera
Raw	7.87 ± 0.093^{c}	8.80 ± 0.0054^{d}	24.4 ± 0.33^{h}	5.29 ± 0.22^{b}
Dried	23.3 ± 0.50^{g}	26.2 ± 0.16^{i}	24.3 ± 0.48^{h}	16.5 ± 0.14^{f}
De-oiled	8.91 ± 0.49^{d}	9.61 ± 0.18^{e}	23.8 ± 0.50^{gh}	4.95 ± 0.0037^{a}

Data represent means.
Means within same without common superscript are different ($P < 0.05$).

and others (2005). Their study reported lower amounts of CO, CH_4, and CO_2. In addition, C_2H_2 and C_2H_6 gases were not detected. However, there was a substantially higher amount (5.2%) of C_2H_4 detected.

Ash describes the amount of material recovered from the ash cleanout port (Bowser and others 2005) and ignores negligible ash resulting from startup pellets. Approximately 1.8% ash was collected from wood pellet gasification (Table 5). Gasification of salmon/pellet mixtures ranged from 1.5% to 2.9%. Dried whole fish produced 7.3% ash. These values are lower than previously reported by Bowser and others (2005). They recovered 6% ash from the wood pellets and 16% ash from the biomass sludge they evaluated.

Tar production (data not reported) varied greatly for the biomass tested and did not appear to be higher for any specific type. According to Quaak and others (1999), tar in syngas from wood gasified in an updraft gasifier ranged 30 to 150 g/Nm^3. Tar production at least in this range could be expected from salmon waste syngas. A system employing syngas combustion for energy production in close proximity to the gasification chamber to maintain gas at a high temperature would allow tar remain in a gaseous state and combust with syngas.

Energy calculations

Table 5 displays the conversion of energy in biomass to syngas. Biomass high heating value (HHV) is the amount of energy loaded in the gasifier as calculated from bomb calorimetry data. Syngas HHV was calculated from the gas chromatograph results and heating values of pure gases taken from Waldheim and Nilsson 2001. The similar gas compositions result in similar high heating values of syngas produced for all treatments mixed with pellets (Table 5). None of the treatments had significantly different high heating values. However, the dissimilar heating values of biomass caused the cold gas efficiencies to be significantly different for dried whole fish (Table 5). This signifies that pellets increased the conversion efficiency of salmon. The relationship between the percentage of pellets in a given biomass mixture and the average HHV of syngas from that mixture is shown in Figure 3.

The percentage gasified is the total weight of the feedstock minus the weight left in ash. Cold gas efficiency is the percentage of energy from biomass that converts to energy in syngas, or the syngas energy divided by the biomass energy (Bowser and others 2005). The cold gas efficiency of mixtures of samples and pellets were not significantly different from the cold gas efficiency for 100% wood pellets. Cold gas efficiency of dried whole fish was approximately

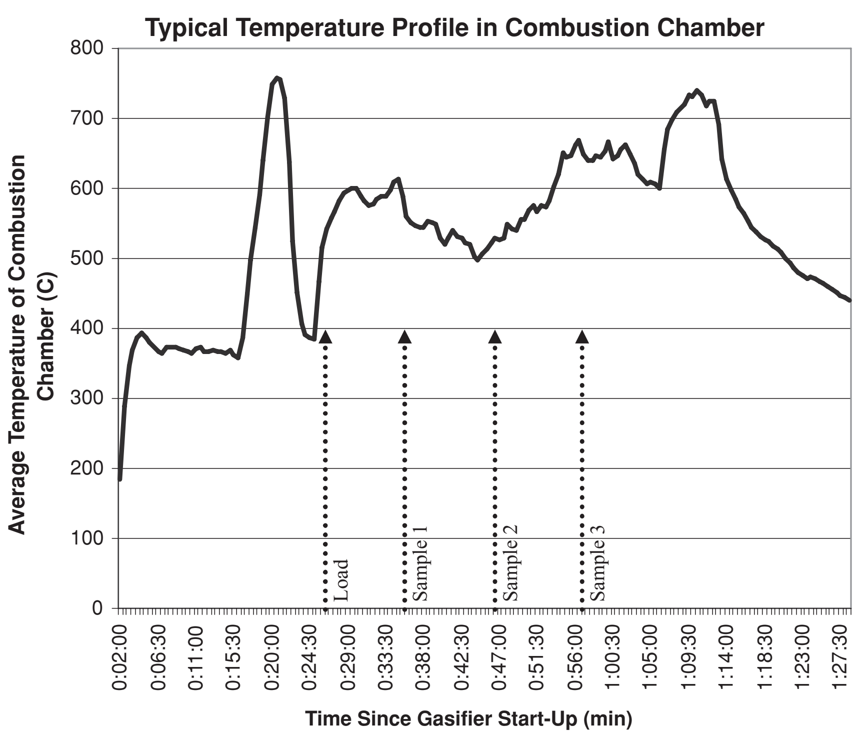

Figure 2—Typical temperature profile for the gasification bed. First spike is during warm-up phase. Loaded biomass 19 min after beginning start-up. Samples taken at 29, 39, and 49 min after beginning start-up.

Table 4—Average gas chromatograph results (% volume) for 1 mL sample of syngas from gasified biomass.

	He	H_2	N_2	O_2	CO	CH_4	CO_2	C_2H_2	C_2H_4	C_2H_6
Pellets	0.00	3.42	66.00	0.98	15.78	1.08	12.48	0.01	0.07	0.07
Whole fish[a]	0.09	2.65	69.20	2.01	9.06	1.33	15.29	0.05	0.20	0.12
Heads[a]	0.00	1.76	71.35	3.15	8.49	1.07	13.92	0.02	0.16	0.08
Viscera[a]	0.03	3.56	67.95	0.73	10.12	1.46	15.75	0.03	0.17	0.11
Frames[a]	0.13	1.74	70.36	3.25	6.56	1.27	15.85	0.22	0.48	0.14
De-oiled heads[a]	0.08	2.63	69.87	1.27	7.60	1.49	16.73	0.05	0.21	0.07
De-oiled frames[a]	0.04	2.22	69.83	2.46	7.22	1.63	16.34	0.02	0.07	0.17
De-oiled whole fish[a]	0.04	2.08	69.20	1.73	7.58	1.54	17.07	0.02	0.57	0.17
Dried whole fish	0.03	1.61	77.11	2.51	5.35	0.61	12.01	0.32	0.35	0.09

[a]Final moisture content 20% when mixed with wood pellets.

Table 5— High heating value (HHV) of gases calculated from bomb calorimetry data (Calc HHV) or from syngas (synthesis gas) and ash (grams) recovered from gasifier.

	Calc HHV (MJ/kg)[B]	Syngas HHV (MJ/kg)	Ash (g)	% Gasified	Cold gas efficiency (%)
Pellets	18.80	2.26[a]	26.5[a]	98.2	27.5[a]
Whole fish[A]	16.26	1.84[ab]	29.7[a]	98.0	25.0[a]
Heads[A]	16.35	1.59[ab]	25.4[a]	98.3	21.7[ab]
Viscera[A]	16.01	1.98[ab]	39.5[a]	97.4	26.0[a]
Frames[A]	16.14	1.80[ab]	41.7[a]	97.2	25.2[a]
De-oiled heads[A]	16.35	1.65[ab]	43.8[a]	97.1	22.5[ab]
De-oiled frames[A]	16.12	1.69[ab]	26.1[a]	98.3	23.5[a]
De-oiled whole fish[A]	16.39	1.84[ab]	22.6[a]	98.5	25.3[a]
Dried whole fish	23.14	1.45[b]	110[b]	92.7	13.6[b]

[A]Final moisture content 20% when mixed with wood pellets.
[B]Not analyzed statistically.
Means within columns without common superscript are different ($P < 0.05$).
Cold gas efficiency describes amount of energy in biomass that converted to energy in syngas.

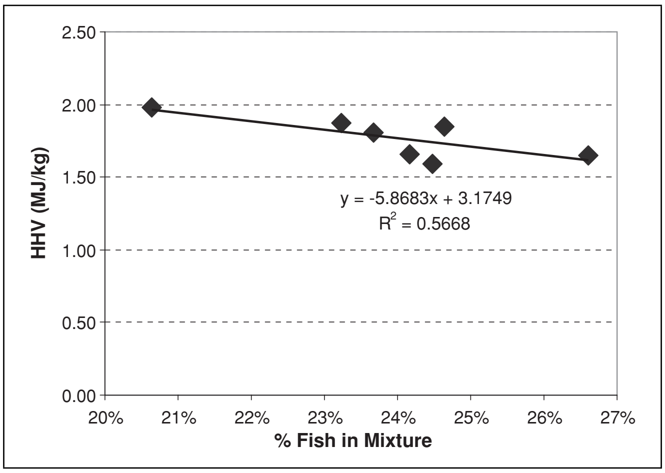

Figure 3—Relationship between the percentage of fish in the gasified mixture and the high heating value (MJ/kg) of the gas produced.

half of that from pellets and mixtures. In general, cold gas efficiencies for pellets and for salmon pellet mixtures were approximately half that reported by Bowser and others (2005). They reported being able to generate cold gas efficiencies of almost 58% from wood pellets using the same gasifier under similar conditions. Sludge and mixtures of sludge and pellets also produced cold gas efficiencies around 50% and 60%, respectively. Composition comparisons between the salmon used in this study and sludge used in the Bowser and others (2005) study point to significant differences in lipid content and protein (much higher for salmon). The protein content of the salmon samples tended to make the mixtures of pellets and salmon sticky. This in turn interfered with how the biomass progressed (flowed) down the combustion chamber. Steady-state temperatures in the biomass bed were difficult to achieve because of a design flaw that created a narrowing where the combustion chamber and biomass bed were sealed together (see Figure 1 in Bowser and others 2005). At this narrowing in the pilot-scale gasifier the biomass would often bridge to the sides of the gasifier. This "bridging effect" would subsequently interfere with its downward progression through the bed to the combustion chamber. The remedy required opening of the charging port to tamp the biomass further down into the combustion chamber. This usually had to be done once during gasification. The bridging of biomass to the sides of the gasifier was likely not a problem for the low protein sludge used in the Bowser and others (2005) study. However, "bridging" was a significant obstacle encountered with the use of the much higher protein products tested in this study and suggests that an alternate gasifier design is needed for higher protein products.

Conclusions

Composition analysis of Red Salmon by-products and pine pellets matches closely with other studies listing moisture or energy content of similar products. Analysis of syngas from pure wood pellets is also very comparable to syngas composition reported in similar studies.

Preliminary observation showed that moisture contents of raw salmon were too high for the biomass to be gasified as-is. Though different types and sizes of gasifiers allow for different ranges of moisture contents of feedstocks, the small-scale, up-draft gasifier used for this experiment was found to produce good quality syngas from salmon by-product with feedstock moisture content only as high as 20%. A larger up-draft gasifier would allow a more accurate study of gasifying salmon waste or mixtures. A larger system would also allow higher moisture content biomass to be tested.

Drying the raw salmon to 20% moisture content will not be feasible in a production setting, so dry biomass was mixed with salmon by-product to lower moisture content. For trial purposes, wood pellets were the drying agent. However, in a production setting, other organic, dry products such as cardboard or lumber mill waste could be used to lower moisture content before gasification. Also, the design of the gasification system should make use of heat lost from the gasifier to drive off excess moisture in feedstock before it is loaded into the gasifier.

Gasification of salmon by-product was successful when mixed with a combustible drying agent. The net balance of energy, analyzed as the cold gas efficiency, was good enough to warrant further investigation as the system used in this study is the least promising scenario. Efficiency will dramatically increase in a larger system, a continuous-feed system, and a tighter system.

The main goal of this study was to determine if salmon waste or mixtures of salmon waste could be gasified to produce syngas. Gasification of these by-products was found to be feasible if moisture content can be reduced or high temperatures in combustion and pyrolysis zones can be maintained. Though the high heating values and cold gas efficiencies obtained from gasified salmon mixtures are not as high as for syngas from a drier, wood-based feedstock, they are high enough for the process to be further evaluated for use in rural salmon fishing villages as a means of waste disposal. Gasifying salmon waste will provide an alternative method of waste disposal that not only keeps waste from being disposed of at sea, but will also provide energy that can be utilized within the fisheries.

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